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Diurnal variations of cloud from ISCCP data

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Abstract

Information on the diurnal cyle of low, mid and high level cloud amount, for the period December 1984 to November 1990, compiled by the International Cloud Climatology Project (ISCCP), is analyzed using complex empirical orthogonal functions applied to the complex envelope of seasonal variations in the diurnal cycle. It is found that previous results on the diurnal variation of cloud amount, obtained from satellite and station data for more restricted periods and regions than that used here, are verified by the ISCCP data. The early afternoon maximum in low level cloud amount over all the world's continental land masses implies that diurnal variability enhances this cloud type's albedo effect. Conversely the nightime and early morning maxima in mid and high level cloud amount, over much of the globe, enhance their greenhouse effect. Any secular change in the diurnal variability of these cloud types could therefore have a significant effect on the net radiation at the Earth's surface.

1. Introduction

Water vapor and clouds of liquid water and ice in the Earth's atmosphere are crucial elements in the determination of the radiative properties of the atmosphere and the sensitivity of the Earth's climate to forcings, both anthropogenic and natural. Clouds play a key role in determining the radiative balance of the Earth, in the hydrological cycle and in the determination of the water vapor distribution in the atmosphere. The increasing concentration of carbon dioxide and other anthropogenic gases in the Earth's atmosphere and their predicted warming effect has led to considerable debate about the magnitude and sign of the cloud feedbacks. These may be expected to act in a warmer climate as a result of changes in the distribution, structure and optical properties of clouds and consequent modifications of the water vapor distribution. These feedbacks are important in the problem of climate change, since the radiative effects of clouds are large compared to virtually all climate forcing mechanisms that have been proposed. The uncertainties associated with cloud feedbacks have been noted in an intercomparison of global circulation models (Cess et al., 1989).

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With regard to the impact of clouds on surface air temperatures, there has been a relatively large decrease in the diurnal temperature range over the United States during the last four to five decades (Karl et al., 1984). This decreased daily temperature range has been statistically associated with an increase in cloud amount, precipitation and decreasing sunshine (Plantico et al., 1990). Although a change in the mean cloudiness can modify the daily temperature range, so might a change in the diurnal variability of cloud. This is because the radiative effect of a cloud type depends on its diurnal phase as well as its height, optical thickness and seasonality (Hartmann and Doelling, 1991). For example, an increase in the magnitude of the diurnal range of low cloud over land, because it peaks in the early afternoon, would increase the effective albedo of the cloud (reflecting solar radiation back to space) without significantly modifying its greenhouse effect (which is a reduction in longwave radiation emitted to space). This would tend to cause cooler daytime maximum temperatures, leaving the nighttime temperature minimum relatively unaffected. It has been suggested that the effect of diurnal cloud variations on the net radiation can be as great as 50 Wm^{-2} (Hartmann et al., 1991). We therefore consider the magnitude and timing of diurnal cloud variations in an attempt to assess their possible impacts on the diurnal cycle of surface air temperature. Previous studies have mainly focused on the analysis of outgoing infrared (IR) radiation which can lead to ambiguities in the assignment of radiances to cloud types. These studies have also been for limited periods and of limited regional extent. In this study the magnitude and phase of the diurnal cycle of cloud types, on a global scale over a six year period, are determined.

2. Data

The dataset used in this study was produced by the International Cloud Climatology Project (ISCCP) and has been described by Rossow and Schiffer (1984). In this dataset clouds are classified according to their optical thickness and cloud top pressure. Since we are interested in diurnal variability, and the ISCCP cloud algorithm requires visible radiances in order to retrieve the cloud optical depth, our clouds are classified by altitude only. Thus our cloud types are high (cloud top pressures below 440 mb), middle (cloud top pressures between 440 and 680 mb) and low (cloud top pressures greater than 680 mb). ISCCP cloud products are available in daily (C1) and monthly mean (C2) versions, with results reported every three hours at 250 km resolution. We have used the C2 version of the ISCCP data which provides information on the monthly mean diurnal cycle in terms of UTC. The data used here covers the period between December 1984 and November 1990 and the analysis is restricted to the region from 60°S to 60°N because of the absence of geostationary satellite coverage at high latitudes. There is also a lack of geostationary satellite coverage over the Indian subcontinent, since Indsat data has not been provided for the ISCCP, and there is therefore a gap in the analysis over this region. At the height of the Himalayan plateau, boundary layer cloud, which is classified as low elsewhere, is classified as mid level cloud. Since boundary layer cloud has a very strong diurnal cycle, the Himalayan plateau is excluded from the analysis to simplify the interpretation of the results.

The variation in the number of geostationary satellites available over the course of the record means that inter- and intra-annual estimates of diurnal variability can be biased by changes in sampling in some parts of the world. For example in March 1987 and in January and February of 1988 there was reduced spatial coverage of the diurnal cycle. In order to minimize this problem we averaged the monthly data up to a seasonal time scale so that we could analyze the seasonal and inter-annual variability of the diurnal cycle.

3. Method of analysis

In order to evaluate the global structure of diurnal variability in cloud it is necessary to convert the UTC data, provided in the ISCCP climatology, to local time (LT). One approach would be to bin each UTC sample at a gridpoint to the three hour LT bin that is nearest. The problem with this approach is that the ISCCP observations have already been sorted according to their nearest three hourly UTC bin and the actual time of observation may therefore differ from the time at the center of the UTC bin by up to an hour and a half. Since rebinning to local time causes the same problem, the original local time of the data samples can be up to three hours different from the local time assigned to them. This means that simply rebinning data to local time can severely alias the diurnal cycle.

This problem can be overcome by using a model for the diurnal cycle, such as a diurnal harmonic, which can be interpolated to the actual local time. Since there is evidence for asymmetries in the diurnal cycle of cloud we did not use a simple harmonic as our model of the diurnal cycle, but, rather, principal components (PC's) of the diurnal variability (Preisendorfer and Mobley, 1988). The PC's allow the diurnal cycle to be represented in terms of a distorted sinusoid which explains the maximum amount of diurnal variance in the data. The PC's are, therefore, both a natural representation and a tool for compression of information about the diurnal cycle. We calculated the PC's separately for each season's climatology, formed from the six years of data available, after the mean over the diurnal cycle had been removed for each grid box. In these climatologies the diurnal cycle was linearly interpolated to half hour resolution in time and shifted to local time (LT). The maximum error caused by rebinning to local time at half hour resolution (an error of 15 min in the LT assigned compared with that given by ISCCP) and the error caused by linearly interpolating are comparable, and are both small compared with the relatively coarse temporal resolution of the data. We found that the global average diurnal cycle is almost the same in all seasons with the first and second PC's being, distorted, quadrature components of the diurnal cycle in seasonal cloud amount and the third and fourth PC's being, distorted, quadrature components of the semi-diurnal cycle in seasonal cloud amount. In order to evaluate the relative contributions of the seasonal mean, the diurnal variation and the semi diurnal variation in cloud amount, to the distribution of cloud over the globe we fitted a model, consisting of a mean (constant), the two diurnal harmonics and the two semi-diurnal harmonics, to the half hour resolution seasonal climatology, for each gridbox and averaged the results over the globe. The percentage of the diurnal signal explained by the different terms in the model is summarized in Table 1. It is apparent that the mean seasonal cloud amount is the dominant term, but the diurnal harmonics still play a significant role in determining the distribution of clouds. We therefore used the two quadrature diurnal harmonic PC's obtained for each cloud type, for Northern Hemisphere winter, to model the diurnal cycle. The season chosen is irrelevant since the correlation between the diurnal harmonic PC's for Northern Hemisphere summer (JJA) and the diurnal harmonic PC's for Northern Hemisphere winter (DJF) is greater than 0.98 for all cloud types. These principal components are shown, for each cloud type, in Fig. 1.

Table 1

Relative contribution of the seasonal mean cloud amount, the diurnal variation of cloud amount and the semi diurnal variation of cloud amount to the distribution of cloud

% Explained		Mean	Diurnal cycle	Semi-diurnal cycle
Low	Summer	76	14	6
	Winter	78	14	5
Mid	Summer	79	12	5
	Winter	80	12	4
High	Summer	76	14	5
	Winter	76	14	6

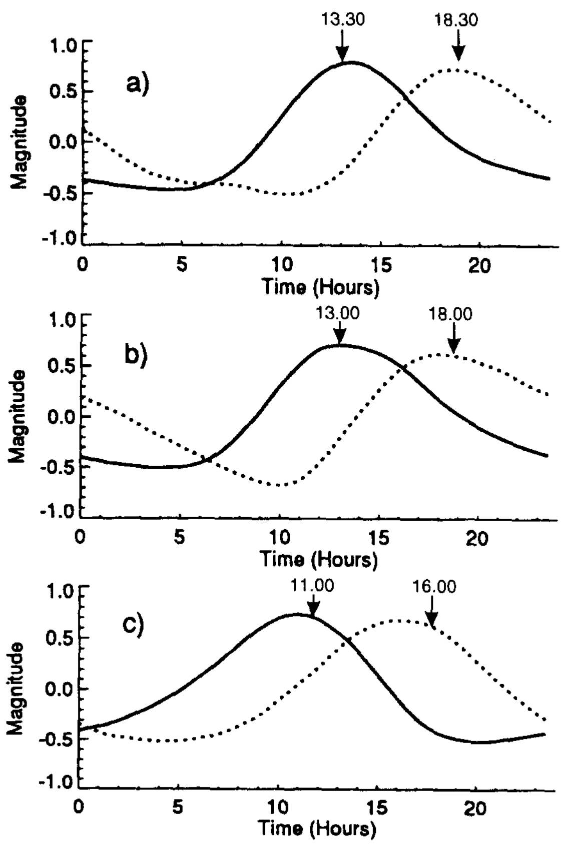

Fig. 1. Distorted diurnal cycles constructed from PCA of Northern Hemisphere climatology for (a) low cloud, (b) mid cloud, (c) high cloud. In the subsequent construction of complex EOF's the projection onto the diurnal cycle represented by solid lines is taken to be real and the projection onto the diurnal cycle represented by dashed lines is taken to be imaginary.

The way in which we used the diurnal harmonics shown in Fig. 1 to analyze the variability of the diurnal cycle in terms of local time is as follows. First the diurnal cycle for each grid-point for each season, for each cloud type, is projected onto each of its respective diurnal harmonics (that is, the solid and dashed lines shown in Fig. 1) yielding two data sets for each cloud type. In these data sets the value at each gridbox for each season represents the diurnal variations of the cloud type associated with the diurnal harmonic PC's used to project out the data. The projection onto the diurnal harmonics is done by multiplying the UTC diurnal cycle data by the values of the diurnal harmonic interpolated to the correct local time for that gridbox. Since the longitudinal extent of a gridbox at 60°N/S is 5° the UTC times at this latitude correspond to local times that are shifted by 20 minutes [$5°/360° \times 24$(hours)] with respect to each other. Thus for large spatial scale variations in the diurnal cycle of cloud amount the ISCCP data has an effective temporal resolution of 20 minutes at 60°N/S and 10 minutes at the equator. The half-hour temporal resolution on which this analysis is based therefore represents a compromise between allowing for the finest temporal resolution and introducing spurious variability. In order to limit distortion of the analysis by missing data we required that the diurnal sampling be complete in order to assign a projection onto the diurnal harmonic, otherwise the data is considered to be missing. Rather than analyzing the variability of the two projected data sets separately we then combine them into a complex valued data set. This is motivated by the fact that the two diurnal harmonics are in quadrature (are orthogonal by construction). Thus, by taking the projection onto one harmonic as the real part of the data and the projection onto the quadrature component as the imaginary part, one can analyze the change in phase and amplitude of the diurnal cycle on inter- and intra-annual time-scales in a compact way. In our analysis the data for a cloud type that has been projected onto its diurnal harmonic PC represented by a solid line in Fig. 1 is taken to be the real part of the complex data set. The data for a cloud type that has been projected onto its diurnal harmonic PC represented by a dashed line in Fig. 1 is taken to be the imaginary part of the complex data set. The complex signal thereby formed is essentially the envelope of variations in the diurnal cycle, which is intimately related to the analytic signals (Born and Wolf, 1984) commonly used in the formation of complex empirical orthogonal functions (CEOF's). The fact that we are analyzing the envelope of a high frequency signal (the diurnal cycle) means that there is no problem in interpreting our results. In general, analytic signals, formed from broadband time-series, are not causal which can lead to problems in interpretation. The final part of the analysis is the formation of CEOF's of the complex data set (Preisendorfer and Mobley, 1988), by a complex singular value decomposition, which isolate the principal modes of variability of the diurnal cycle, for the three cloud types, on a global basis. The results obtained can be checked against previous studies that used infrared radiance data and against station data.

Although the semi-diurnal cycle is of some interest with regard to aliasing and bias in satellite measurements we have not analyzed it here, because of stricter requirements on missing data and its consequent sensitivity to variations in satellite sampling on an inter-annual time-scale. If adequate data were available the esoteric mathematical formalism of quaternions (Preisendorfer and Mobley, 1988) could be applied to a unified analysis of the diurnal and semi diurnal cycles.

4. Results

Our results are presented in the form of maps (CEOF's), that, when taken in conjunction with the diurnal harmonics presented in Fig. 1, provide information on the amplitude and phase of the diurnal cycle. Although the diurnal harmonics presented in Fig. 1 for the different cloud types have slightly different phases and shapes, to a good approximation the diurnal harmonics represented by a solid line have a peak near noon and the diurnal harmonics represented by a dashed line have a peak in the early evening. In the plots (of CEOF's) that follow we represent the complex values by a vector with the vertical projection of the vector being the real part (positive up) and the horizontal projection of the vector being the imaginary part (positive to the right). If we recall that the projection of the data onto the diurnal harmonic represented by a solid line (peak near noon) was taken to be real and the projection of the data onto the diurnal harmonic represented by a dashed line (peak in the early evening) was taken to be imaginary then the meaning of the vectors is: upwards if the peak of the diurnal cycle is near noon; to the right if the peak in the diurnal cycle is in early evening; down if the peak in the diurnal cycle is near midnight and to the left if the peak in the diurnal cycle is in the morning. This explanation presumes that there is no variation in phase, or amplitude of the diurnal cycle over the course of the record which is not true of all the CEOF's, but is true for the CEOF's shown in Fig. 2. Fig. 2 shows CEOF's of the annual average state of the diurnal cycle for the three cloud types. Given that the peak to peak amplitude of the diurnal harmonics shown in Fig. 1 is close to unity the maps (CEOF's) in Fig. 2 are normalized such that the labelled vector in the lower left hand corner of each map provides a scale indicating the peak to peak diurnal variation in cloud amount represented by the vectors.

The annual average diurnal cycle of low cloud amount shown in Fig. 2 has a diurnal peak over land near noon (arrows up) and a diurnal peak over the ocean in the early morning (arrows down and to the left). Recalling that for low cloud the real part of the complex data is constructed by projection onto the solid line in Fig. 1a and the imaginary part by projection onto the dashed line in Fig. 1a we can be more specific about the timing of the peaks in the diurnal cycle. Over land there is a well defined maximum in the diurnal cycle close to 13:30 LT over most of the globe, while a broad oceanic maximum in the diurnal cycle occurs at 08:00 LT, this maximum being around an hour later over the Namibian stratus deck and an hour earlier over the Californian stratus deck. The morning maximum in low cloud over oceans that we find for our six year record agrees with the observations of Short and Wallace (1980) for the two seasons, summer 1975 and winter 1976. Both the timing and width of the morning maximum in low cloud over oceans also agrees with in situ measurements of cloud and modelling studies of boundary layer cloud (Brill and Albrecht, 1982).

A significant cloud type for the tropics, which is observed in this and other studies (Duvel, 1989), is the mid level cloud that has its maximum at sunrise. Such behavior is prevalent over much of tropical South America and Africa. This cloud type is of interest, because its diurnal phase enhances its greenhouse effect at the expense of its albedo effect, causing warming of the tropics. Furthermore the nature and origin of these mid level clouds is unclear. In Fig. 2 the annual average state of the diurnal cycle in mid level cloud is shown. It is apparent that away from the equator the peak in the diurnal cycle of mid level cloud

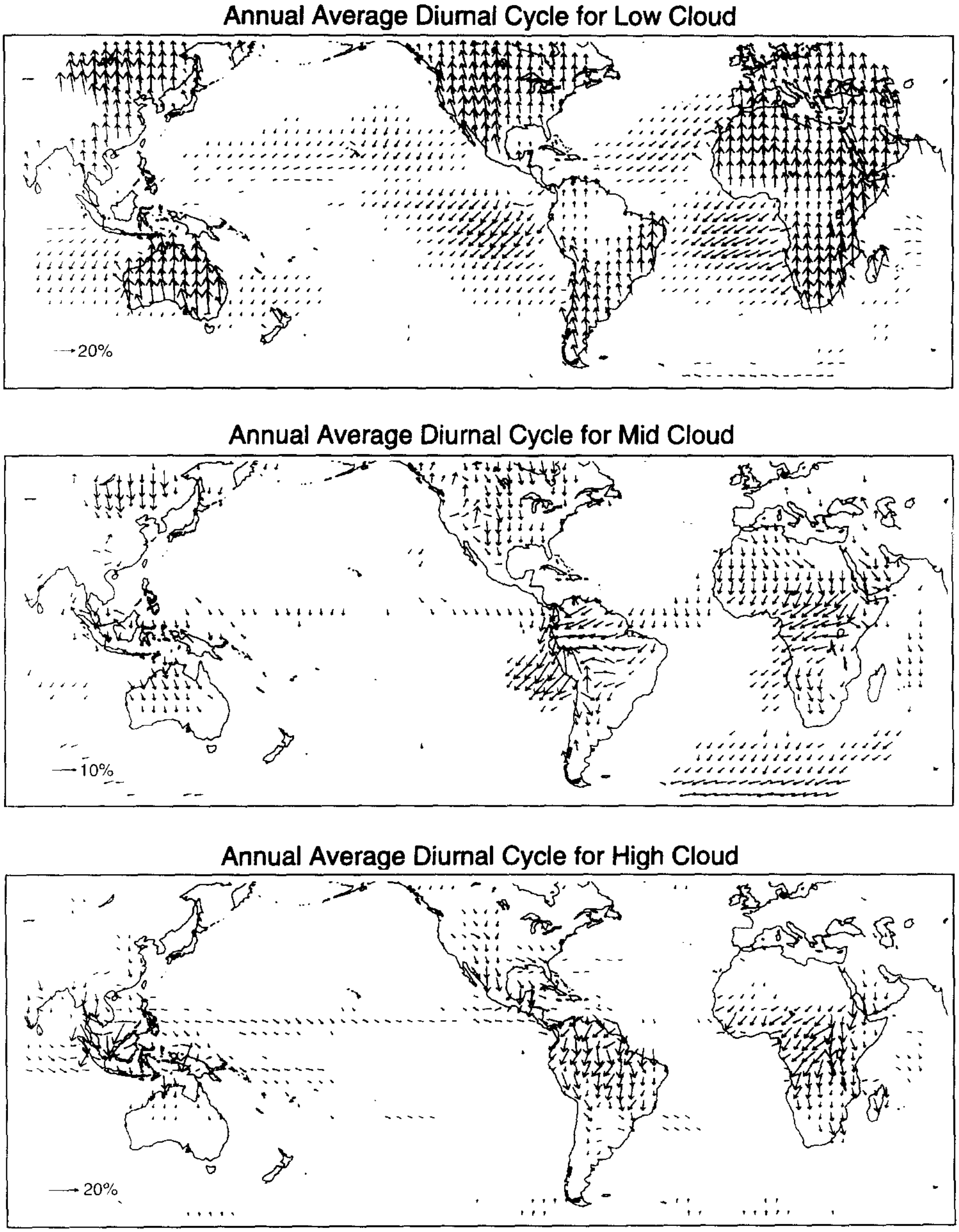

Fig. 2. Complex Empirical Orthogonal Functions (CEOF's) for the average diurnal cycle of low, mid and high cloud, as labelled. Vectors pointing upward represent a maximum in the diurnal cycle near noon. The phase of the maximum in the diurnal cycle gets later as the direction of the vectors moves clockwise, so that a vector pointing downwards represents a maximum in the diurnal cycle near midnight. The scale of the peak to peak diurnal variation in the different cloud amounts is indicated in the lower left hand corner of each map.

amount over land is around 05:00 LT with the cloud amount increasing slowly to around 05:00 LT and then decreasing more rapidly after sunrise (cf. minimum of the solid line in Fig. 1b). The phase of this maximum gets later to around 09:00 LT as one moves toward the equator. Over the areas of the Southern Hemisphere stratus decks the mid level cloud has a maximum in its diurnal cycle at around 07:00. In the ITCZ the peak in the diurnal cycle of mid level cloud amount is near 05:00.

The annual average state of the diurnal cycle in high cloud can be determined from Fig. 1c and Fig. 2. Over tropical Africa and South America there is a peak in the diurnal cycle of high cloud amount at night, or in the early morning. This peak is around 20:00 LT away from the Equator and gets later, to around 24:00 LT near the Equator. A study of high cloud in the tropics, in summer, based on IR radiances indicates that the peak in high cloud over land should occur between 18:00 and midnight LT, with considerable regional variability (Duvel, 1989), which result is born out by our own study. The ITCZ, the South Pacific convergence zone (SPCZ) and the South Atlantic convergence zone (SACZ) all have an early evening (16:00 to 20:00) peak in high cloud amount. Over the tropical oceans the early evening peak in high cloud also agrees with the study of Duvel (1989), who also observed that the high cloud has a secondary maximum in the morning over the ocean. This morning maximum appears to be related to the formation of deep convective towers, while the afternoon maximum is related to the subsequent formation of large scale cirrus anvil (Fu et al., 1990). An early evening peak in the diurnal cycle of high cloud amount is also found over the western and eastern USA and Australia, with peak around 20:00 LT over the Rocky Mountains and Australia and a peak around 16:00 LT over the south eastern USA.

The interpretation of the summer/winter and spring/fall maps shown in Figs. 3 and 4, except for the spring/fall variation of high cloud in Fig. 4, is relatively simple. When the real and imaginary parts of the principal components associated with the CEOF's are plotted it is apparent that the variation in phase of the diurnal cycle over the course of a year, both for spring/fall variability and for summer/winter variability, is weak. Since the complex phase of the CEOF's and the principal components is arbitrary to within a constant phase that can be added to the principal component and subracted from the CEOF, any fixed phase shift in the principal component can be absorbed into the CEOF. The effect of these manipulations is that the phase and amplitude of the diurnal cycle in JJA is the vector sum of the annual average CEOF and the summer/winter CEOF. The phase and amplitude of the diurnal cycle in DJF is the vector sum of the annual average CEOF and the summer/winter CEOF multiplied by negative one (i.e. the vectors in the summer/winter CEOF should be rotated by 180° in this case). The phase and amplitude of the diurnal cycle in MAM is the vector sum of the annual average CEOF and the spring/fall CEOF. The phase and amplitude of the diurnal cycle in SON is the vector sum of the annual average CEOF and the spring/fall CEOF multiplied by negative one (i.e. the vectors in the spring/fall CEOF should be rotated by 180° in this case). The only exception is the SON diurnal cycle of high cloud for which the phase and amplitude of the diurnal cycle is the vector sum of the annual average CEOF and the vectors in the spring/fall CEOF rotated by 270°. The magnitude of the peak to peak diurnal variation in cloud amount that the vectors represent is once again indicated by the arrows in the lower left hand corner of the maps.

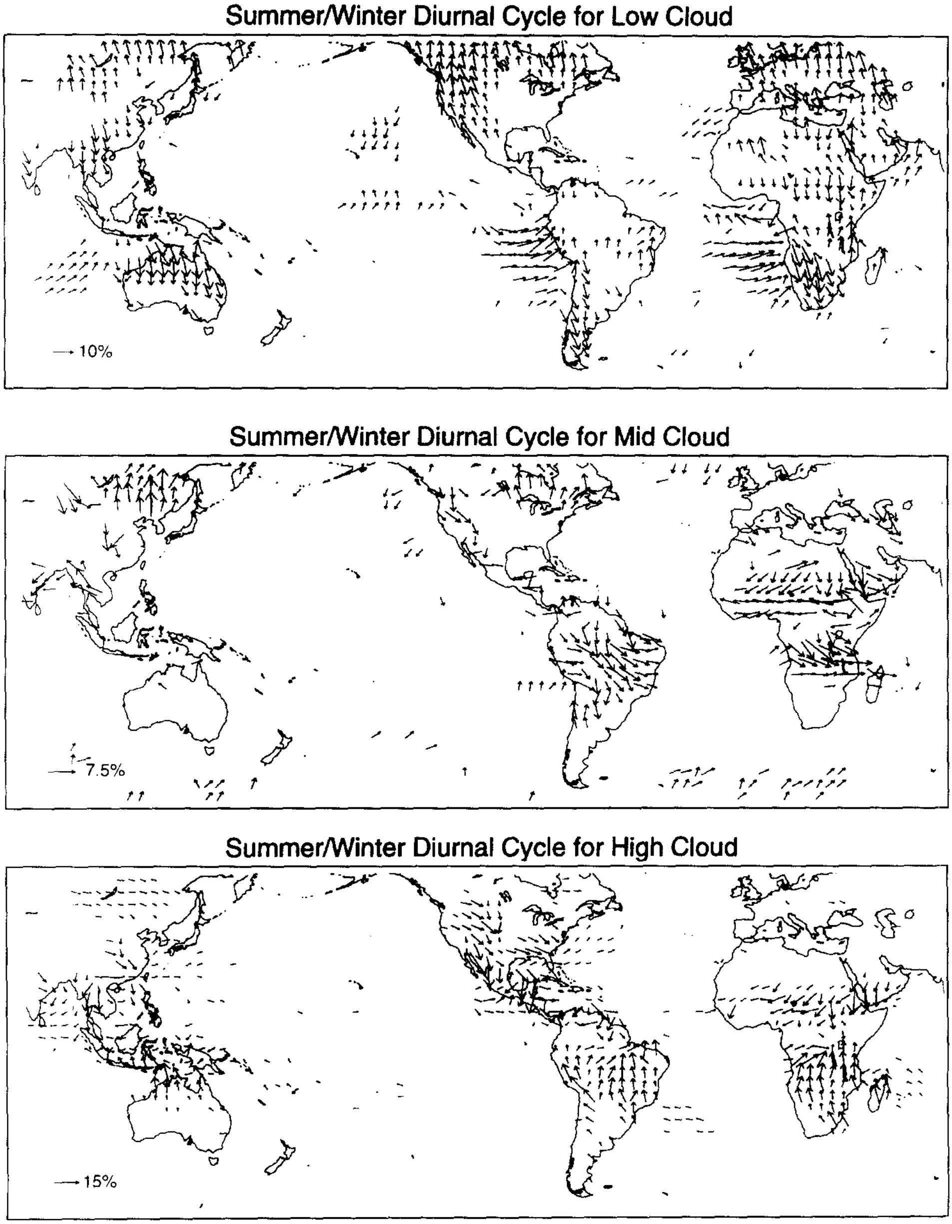

Fig. 3. CEOF's of the summer/winter variation of the diurnal cycle for low mid and high cloud, as labelled. See text for interpretation. The scale of the peak to peak diurnal variation in the different cloud amounts is indicated in the lower left hand corner of each map.

The summer/winter diurnal cycle of low cloud amount shown in Fig. 3 provides a simple example of interpreting these maps. In JJA in the Northern hemisphere extratropics the vectors are pointing in the same direction as those for the annual average diurnal cycle,

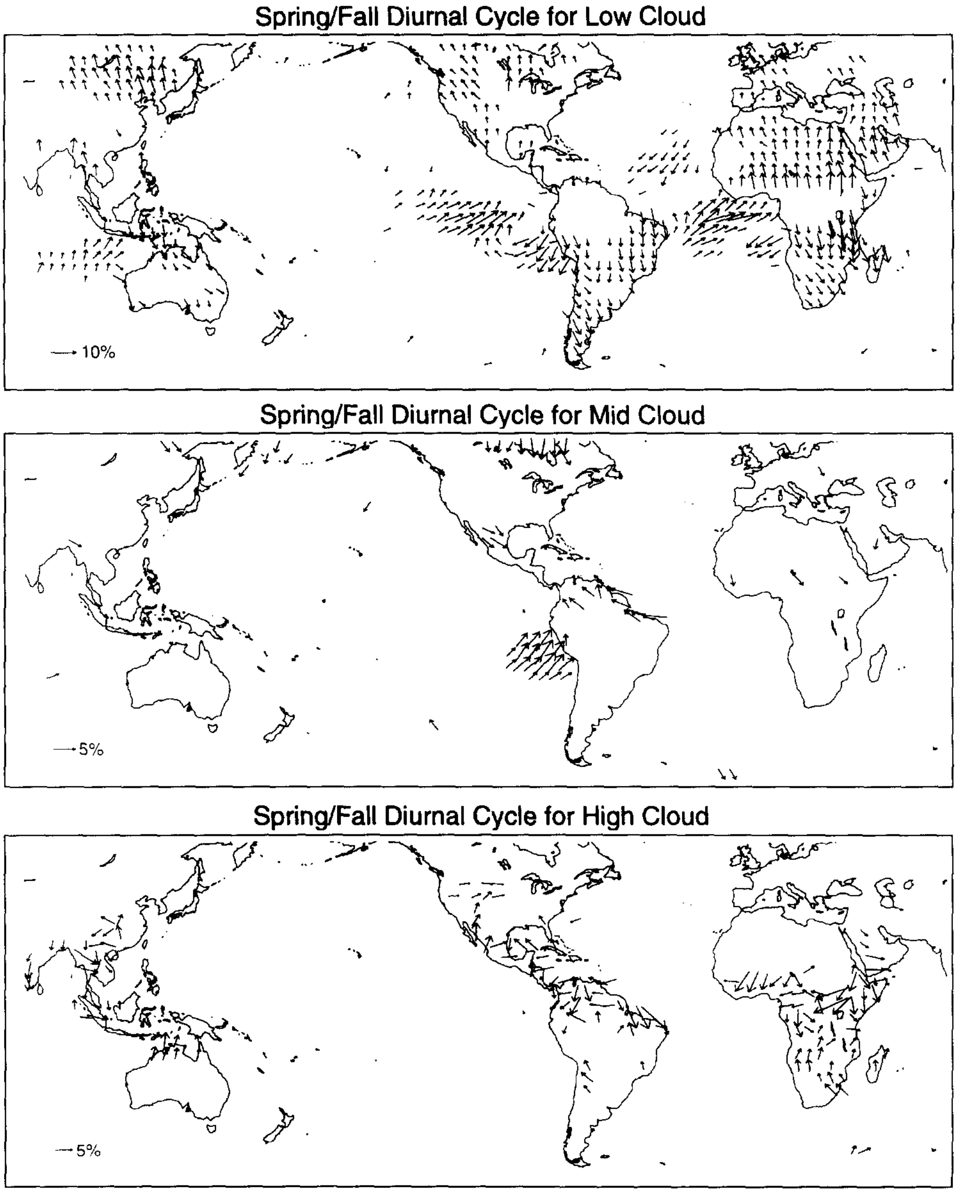

Fig. 4. CEOF's of the spring/fall variation of the diurnal cycle for low mid and high cloud, as labelled. See text for interpretation. The scale of the peak to peak diurnal variation in the different cloud amounts is indicated in the lower left hand corner of each map.

indicating that the strength of the diurnal variation in low cloud amount is enhanced in JJA in the Northern Hemisphere. To determine the modification of the diurnal cycle for DJF the vectors in the summer/winter map of low cloud should be rotated by 180°, in which case, in the Northern Hemisphere extratropics, the vectors would be pointing in the opposite direction to those for the annual average diurnal cycle, indicating that the strength of the diurnal variation in low cloud amount is decreased in DJF in the Northern Hemisphere. A similar modification of the strength of the diurnal cycle is true in the Southern Hemisphere extratropics, with the diurnal cycle being enhanced in DJF (Southern Hemisphere summer) and suppressed in JJA (Southern Hemisphere winter). In the tropics, particularly India, South East Asia, Africa, South America and the ITCZ the opposite is true, with the diurnal cycle being enhanced in the winter hemisphere and suppressed in the summer hemisphere. One possible explanation for this is the shift of convective activity into the summer hemisphere in the tropics which produces high cloud. As a result of the strong convection high cloud is probably formed in preference to low, boundary layer, cloud and will also mask the low cloud from observation by satellite in the summer hemisphere in the tropics.

The summer/winter diurnal variability of mid level cloud amount shown in Fig. 3 is not as coherent as that for low cloud amount, showing much more regional variability in the phase and amplitude of the diurnal cycle with season over Africa and South America. The overall sense of the change in the diurnal cycle between summer and winter over Africa and South America is that the diurnal cycle strengthens and has a later peak in the summer hemisphere and weakens and has an earlier peak in the winter hemisphere. The details of this behavior, for JJA and DJF, can be evaluated by performing the vector addition of the vectors in the annual average map of the diurnal cycle (Fig. 2) and the vectors in the summer/winter map of the diurnal cycle (Fig. 3), noting that the scale for the annual average map of the diurnal cycle in mid cloud is 10% and that for the summer/winter map is 7.5% (cf. Figs. 2 and 3). Conversely the diurnal cycle of mid level cloud amount is larger in winter over the northeastern Americas and northeastern Asia. The diurnal cycle of mid level cloud over the oceans is enhanced in the summer hemisphere and would appear to be related to the formation of large scale marine stratus over these oceans in the summer hemisphere.

The picture of summer/winter variability in the diurnal cycle of high cloud amount (Fig. 3) is fairly uniform over the whole globe, with the magnitude of the diurnal cycle being greater in the summer hemisphere. The diurnal variability of summertime high cloud should be associated with the diurnal variability in thunderstorm frequency. A final check of the validity of the results given here can therefore be obtained from an analysis of the diurnal frequency of thunderstorms in summer compiled by Rasmussen (1971). This analysis used 294 stations, with records covering 7 to 20 yr for the contiguous United States. The maximum in thunderstorm activity in afternoon and early evening over much of the United States and the anomalous late night/early morning maximum extending southwestward from the Great Lakes are both observed in our analysis of the diurnal variability of high cloud. The magnitude of the diurnal cycle in high cloud over the United States in summertime also compares favorably with that observed in another satellite based analysis (Meissner and Arkin, 1987).

The spring/fall variation in the diurnal cycle of low cloud amount (Fig. 4) is such that there is generally an increased magnitude in the diurnal cycle in the spring hemisphere. The two notable exceptions are the increase in magnitude of the diurnal cycle of low cloud amount in the Southern Hemisphere fall (MAM), over the two Southern Hemisphere stratus decks. If we look at the spring/fall variation in the diurnal cycle of mid cloud amount (Fig. 4), spatially this corresponds to an increase in the magnitude of the diurnal cycle of mid level cloud over the Peruvian stratus deck in Southern Hemisphere spring (SON). The increased magnitude of the diurnal cycle of mid level cloud amount in SON and the decreased magnitude of the diurnal cycle in low level cloud amount in SON over the area of the Peruvian stratus deck indicates that clouds appear to be forming higher in this season. It is perhaps also worth noting that it is in SON that the mean stratus cloud amount has its maximum for the Peruvian stratus deck region. The spring/fall variation in the diurnal cycle of high cloud amount is weak, but interesting in that the principal component associated with this CEOF indicates that there is a change not just in amplitude, but in phase, of the diurnal cycle of high cloud amount over the course of the year. This is related to the areas of strongest convection following the sun, so that the phase of the diurnal cycle of high cloud amount in the tropics in a particular location will vary over the course of a year as shown in this CEOF. It should however be noted that the scale for the vectors in the map of summer/winter variability of the diurnal cycle of high cloud is 15% while that for the spring/fall variability of the diurnal cycle of high cloud is 5%. The variation over the course of a year in the diurnal cycle of high cloud amount is therefore dominated by the changing diurnal amplitude in the summer and winter seasons.

The method of analysis that we have used here may appear needlessly complicated for the determination of the climatological diurnal variability of low, mid and high level cloud amounts. However we hope that in future it may be of use in the analysis of interannual variations in the diurnal and semi-diurnal cycles of cloud amount. Unfortunately in the current version of the ISCCP data the drift in navigation of Meteosat (the geostationary satellite over Africa and Europe) tends to contaminate the analysis of diurnal variability on an interannual time scale. Nonetheless, if one restricts ones attention to the Pacific there is an evident signal of El Niño/Southern Oscillation in 1987 (with suppression of the diurnal cycle of low cloud in the central Pacific where convection occurs) and La Niña in 1988 with enhanced low cloud formation, and diurnal cycle of low cloud, over the cold tongue region). Evidently, one needs to take account of changes in satellite coverage (which is documented by missing data flags) when using the ISCCP diurnal cycle data. The problem with the navigation of Meteosat will be taken care of in the reprocessed version of the ISCCP data set, till which time, if one wishes to analyze interannual variability in the diurnal cycle of cloud amount over Africa and Europe, one should mask out the coastlines. This is because it is the large difference in diurnal cycle between land and water that causes problems if the satellite naviagation drifts.

5. Conclusions

Low level cloud has a significant diurnal cycle with a maximum at around 13:30 LT over almost all of the continental land masses. Such a phase of the diurnal cycle tends to enhance the albedo effect of low clouds over land. These low clouds are boundary layer clouds and so the increasing availability of aerosols as cloud condensation nuclei might well increase both the mean and the magnitude of the diurnal cycle of low cloud amount. This would tend to reduce the diurnal cycle in surface air temperature, because of the effect on the albedo. Over oceans low clouds tend to have an early morning maximum which suppresses the albedo effect of the clouds. It is perhaps worth noting that the Californian stratus deck and trade cumulus appear to be anomalous in the variation of their diurnal cycle of cloud over the course of the year, compared with the regions of stratus decks and trade cumulus throughout the rest of the world. The diurnal maximum in mid level cloud amount over almost the whole globe is either in the early morning or late at night. This means that the diurnal cycle tends to enhance the greenhouse effect of these clouds, while suppressing their albedo effect. The same is true for high level clouds whose diurnal maximum tends to be in the evening or at night over much of the globe. The fact that the spatial variation in the phase of these two cloud types over the tropical land masses follows each other, with the peak in the diurnal cycle of mid level cloud amount always being around nine hours after the peak in the diurnal cycle of high cloud amount indicates that the mid level clouds are probably largely made up of altocumulus, or altostratus clouds that spread during the night as the high level cloud dissipates.

Thus the net effect of diurnal variations in these cloud types, over land, is to cool the surface during the day (low cloud) and warm the surface at night (mid and high cloud). The fact that the phase and amplitude of the diurnal cycle can vary seasonally and is different for different cloud types suggests that there will be different responses to climate change associated with different cloud types (Carlson and Wolf, 1993). If a changing climate modifies the diurnal variability of the different cloud types this could have a significant impact on the net radiation at the surface even if the mean cloud properties remain the unchanged. The ISCCP dataset used in this study, unlike those used in previous analyses, provides global coverage, adequate diurnal sampling, classification into cloud types and is readily available to the scientific community. In this survey we have verified, using other satellite based analyses and ground stations, that the ISCCP climatology provides useful and accurate information about the diurnal cycle in low, mid and high level cloud amounts. This information could provide a sensitive test as to whether General Circulation Models (GCM) have the correct cloud formation mechanisms and lifetimes for the clouds they form. This is an important aspect of GCM development, since the uncertainty in the sign and magnitude of cloud feedbacks in a doubled CO_2 scenario is a principal source of uncertainty in the magnitude of the realized warming.

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References

Born, M. and Wolf, E., 1984. Principles of Optics. Pergamon Press, New York.

Brill, K. and Albrecht, B., 1982. Diurnal variation of the trade wind boundary layer. Mon. Weather Rev., 110: 601–613.

Carlson, B.E. and Wolf, A.B., 1993. Spatial and temporal characterizatio of diurnal cloud variability. In: Proc. 4th Symp. Global Change Studies, Anaheim, CA. Am. Meteorol. Soc., Boston.

Cess, R.D., Potter, G.L., Blanchet, J.P., Boer, G.J., Ghan, S.J., Kiehl, J.T., Le Treut, H., Li, Z.-X., Liang, X.-Z., Mitchel, J.F.B., Morcrette, J.-J., Randall, D.A., Riches, M.R., Roeckner, E., Schlese, U., Slingo, A., Taylor, K.E., Washington, W.M., Wetherald, R.T. and Yagai, I., 1989. Interpretation of cloud–climate feedback as produced by 14 atmospheric general circulation models. Science, 245: 513–516.

Duvel, J.P., 1989. Convection over tropical Africa and the Atlantic ocean during northern summer. Part I: Interannual and diurnal variations. Mon. Weather Rev., 117: 2782–2799.

Fu, R., Del Genio, A.D. and Rossow, W.B., 1990. Behavior of deep convective clouds in the tropical pacific deduced from ISCCP radiances. J. Clim., 3: 1129–1152.

Hartmann, D.L. and Doelling, D., 1991. On the net radiative effectiveness of clouds. J. Geophys. Res., 96: 869–891.

Hartmann, D.L., Kowalewsky, K.J. and Michelsen, M.L., 1991. Diurnal variations of outgoing longwave radiation and albedo from ERBE scanner data. J. Clim., 4: 598–617.

Karl, T.R., Kukla, G. and Gavin, J., 1984. Decreasing diurnal temperature range in the United States and Canada from 1941 through 1980. J. Clim. Appl. Meteorol., 23: 1489–1504.

Meissner, B.N. and Arkin, P.A., 1987. Spatial and annual variations of large-scale tropical convective cloudiness and precipitation. Mon. Weather Rev., 115: 2009–2032.

Plantico, M.S., Karl, T.R., Kukla, G. and Gavin, J., 1990. Is recent climate change across the United States related to rising levels of anthropogenic greenhouse gases. J. Geophys. Res., 95: 16,617–16,637.

Preisendorfer, R.W. and Mobley, C., 1988. Principal Component Analysis in Meteorology and Oceanography. Elsevier, New York.

Rasmussen, E.M., 1971. Diurnal Variation of Summertime Thunderstorm Activity over the U.S. Tech. Note 71-4, USETAC, USAF, Scott AFB, IL 62225.

Rossow, W.B. and Schiffer, R.A., 1984. ISCCP cloud data products. Bull. Am. Meteorol. Soc., 72: 1–20.

Short, D.A. and Wallace, J.M., 1980. Satellite-inferred morning-to-evening cloudiness changes. Mon. Weather Rev., 108: 1160–1168.